Battery and Fuel Cell Development Goals for the Lunar Surface and Lander

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Presented at the Space Power Workshop, April 23, 2008, Huntington Beach, California.

Abstract
NASA is planning a return to the moon and requires advances in energy storage technology for its planned lunar lander and lunar outpost. This presentation describes NASA's overall mission goals and technical goals for batteries and fuel cells to support the mission. Goals are given for secondary batteries for the lander's ascent stage and suits for extravehicular activity on the lunar surface, and for fuel cells for the lander's descent stage and regenerative fuel cells for outpost power. An overall approach to meeting these goals is also presented.

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Space Power Workshop
April 23, 2008
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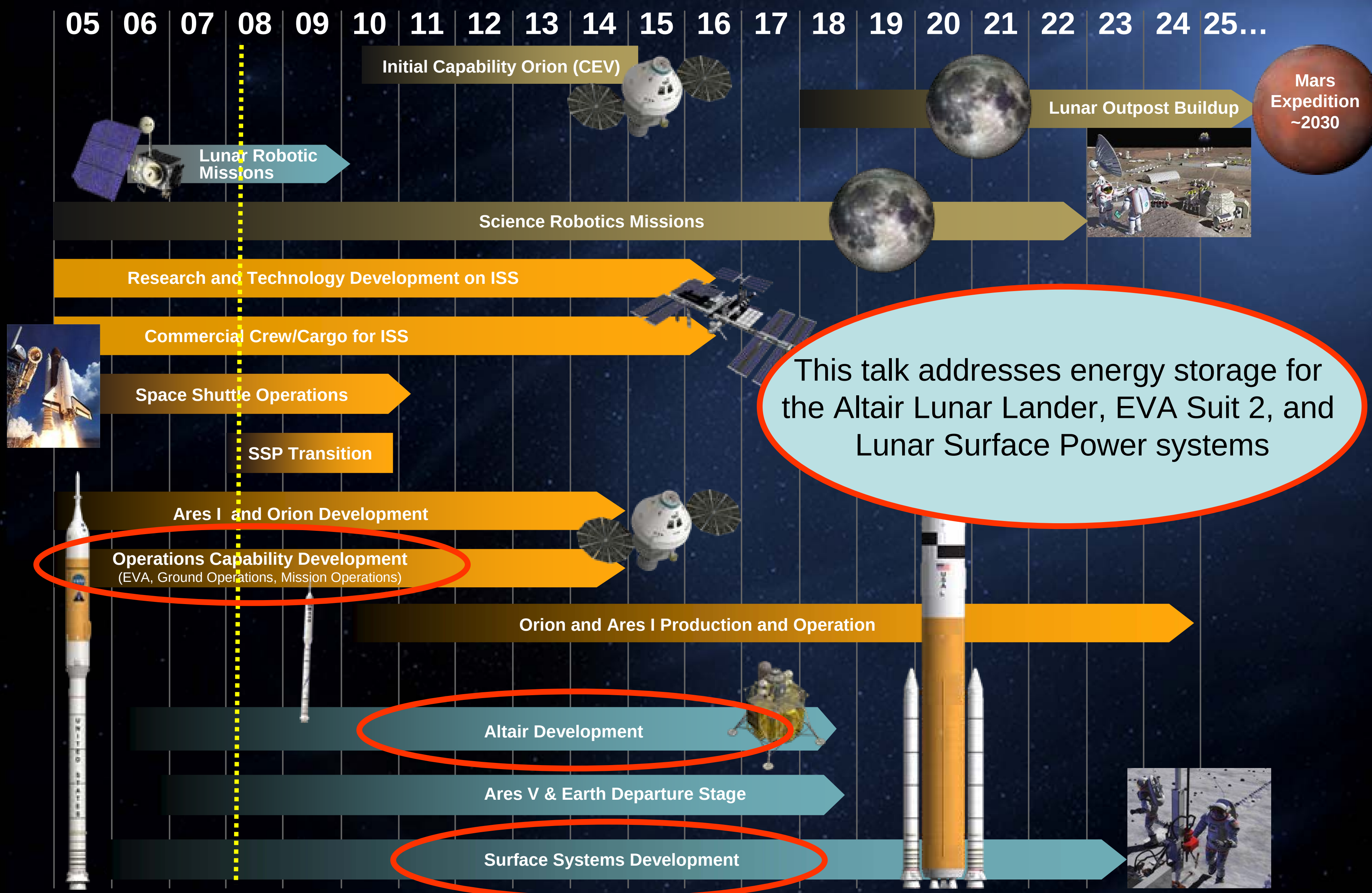
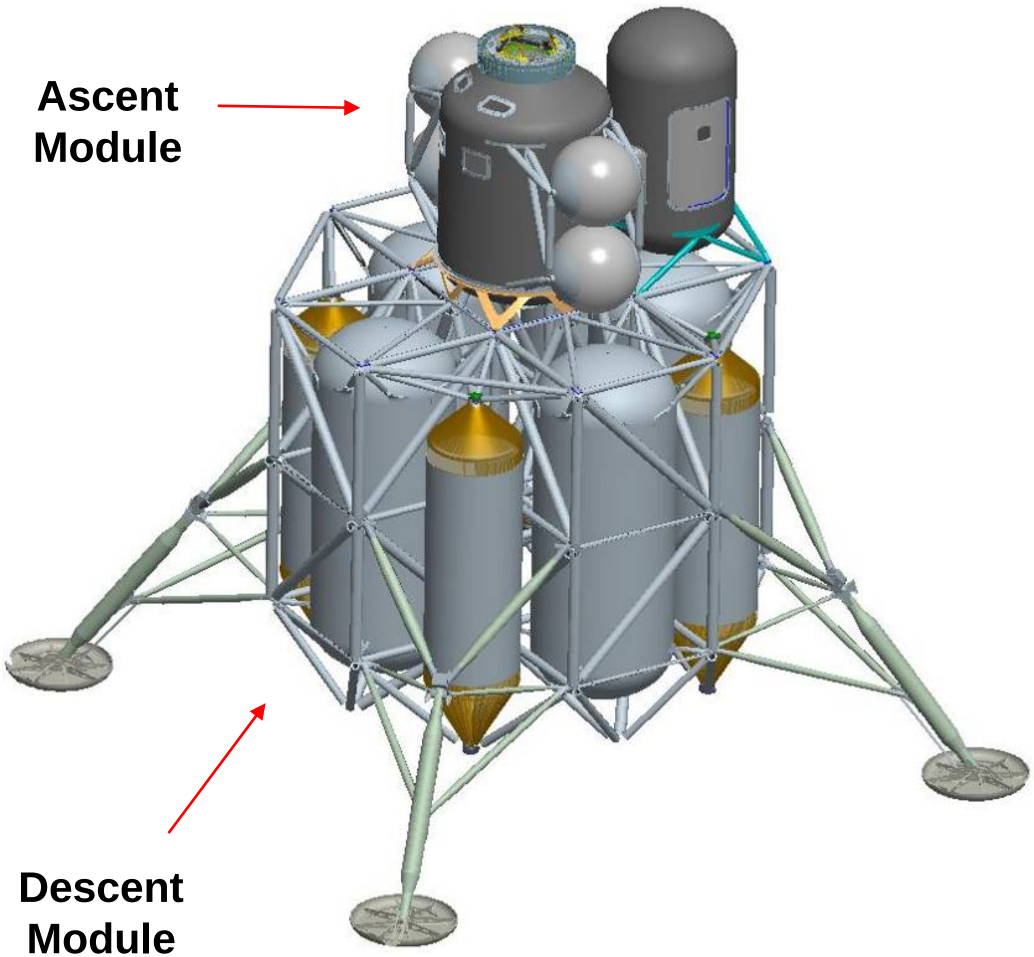
NASA’s Exploration Roadmap



Altair Lunar Lander

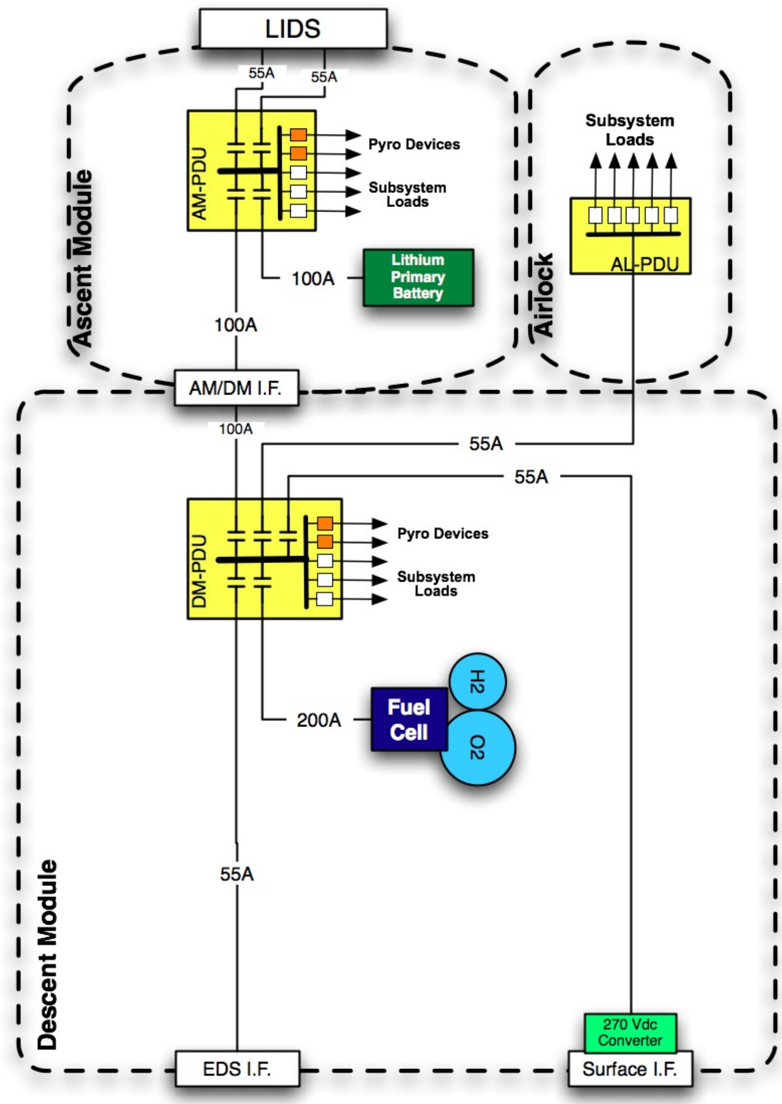


Altair Lunar Lander

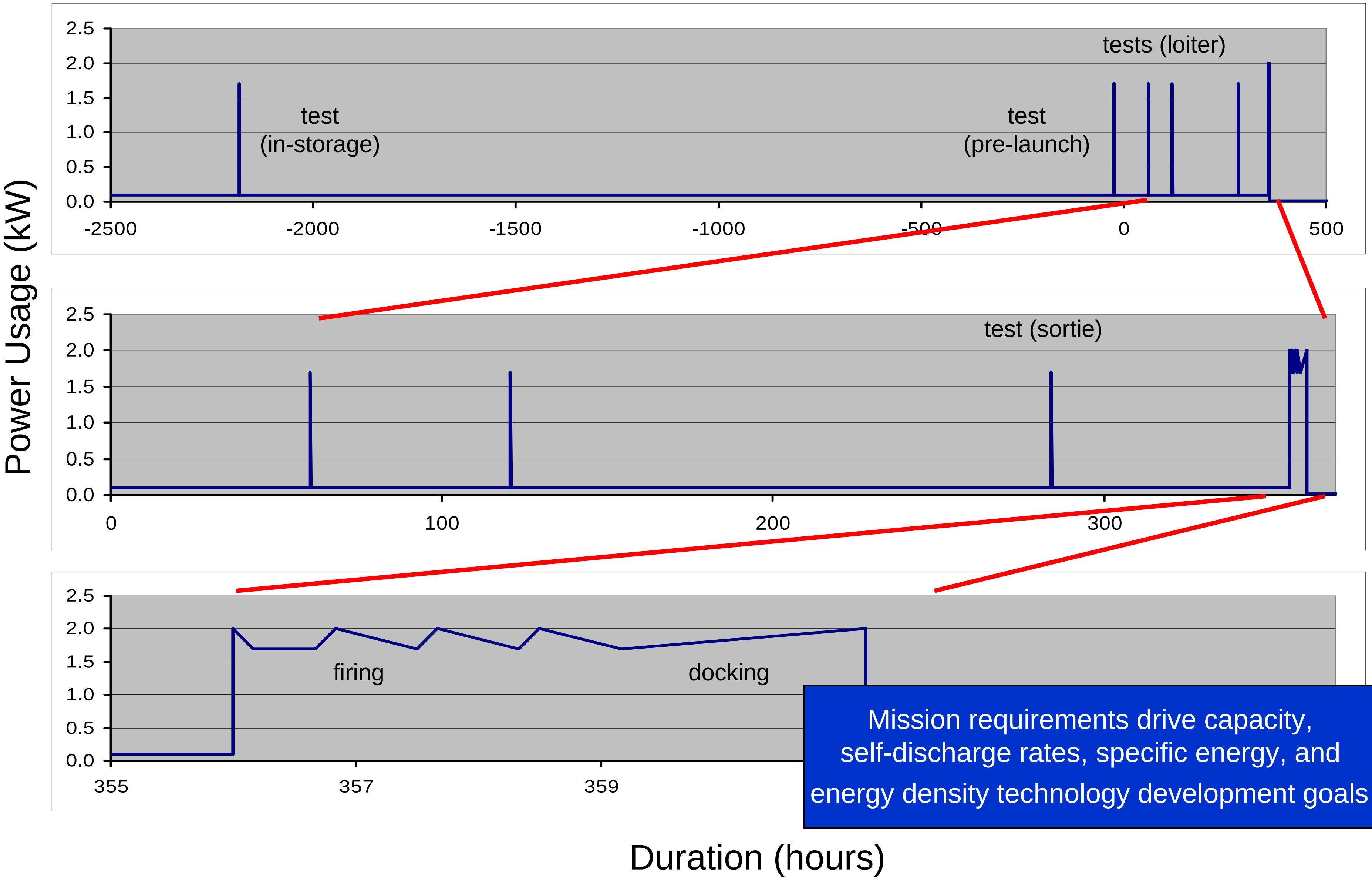
Preliminary information from “minimally functional” DAC1 design (zero fault tolerant)
Abort and contingency scenarios still to be addressed

- **Ascent Module and Airlock**
  - Single primary battery, $LiMnO_2$ chemistry, 14.2 kW-hr capacity
  - Secondary battery desirable to provide instantaneous power for ascent in case descent stage is ejected during abort; and to provide make-up power during shadow phase of TLI.
- **Descent Module**
  - PEM fuel cell, 5.5 kW peak production
  - Provides ascent and descent module power for LLO and surface operations
    - Orion provides 1.5 kW when docked
  - Propulsion residuals provide reactants for surface operations

Key mission requirements:
Human-safe, reliable operation;
high energy density; architecture compatibility



Converting Constellation Architecture into Tech Development Goals
Example: Lunar Ascent Stage (nominal mission)



Mission requirements drive capacity, self-discharge rates, specific energy, and energy density technology development goals

Lunar EVA Suit: “Configuration 2”

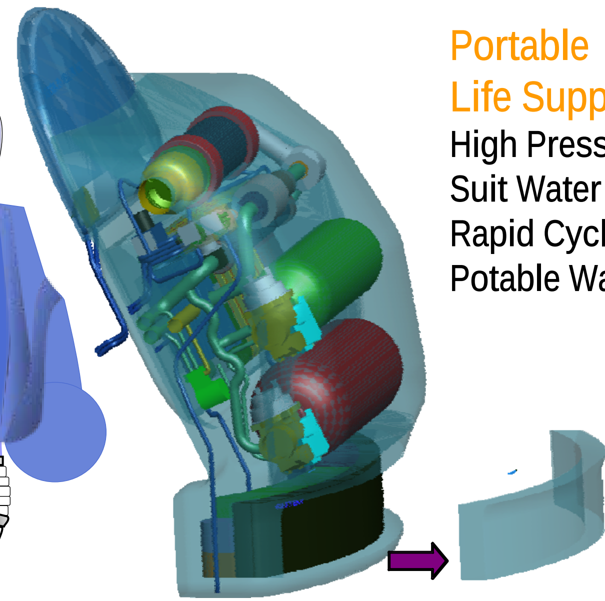
Greatly increased electronic capability (HDTV, communications node, displays, etc…) drives need for high energy batteries in small, low-mass package.

Very high specific energy and energy density with 8-hour, human-safe operation drives technology development.

Power / Communications, Avionics & Informatics (CAI):

Lithium Ion Batteries
Cmd/Cntrl/Comm Info (C3I) Processing
Expanded set of suit sensors
Advanced Caution & Warning

Displays and Productivity Enhancements



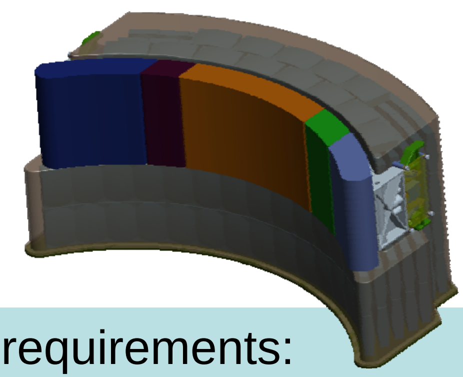
Portable Life Support System (PLSS):

High Pressure GOX
Suit Water Membrane Evaporator
Rapid Cycle Amine
Potable Water in PLSS Tank

Preliminary Battery Requirements:

~ 900 W-Hr energy, delivered
~ 100 W average and 175 W peak power
Current mass allocation: 5 kg
Current volume allocation: 1.6 liter
100 cycles (operation every other day for six months)

Power to support 8 hour EVA provided by battery in PLSS

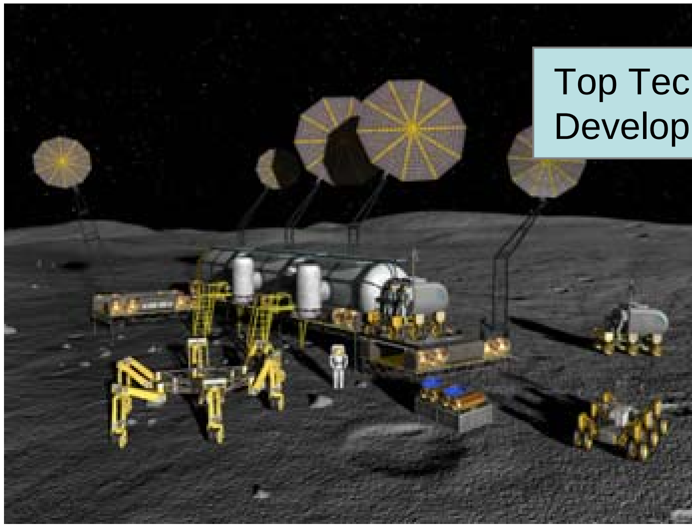


Prioritized mission requirements: Human-safe operation; 8-hr duration; high specific energy; high energy-density.

Lunar Surface Systems

Goal: Continuous human presence on surface

Plan for polar site, but keep capability to go anywhere

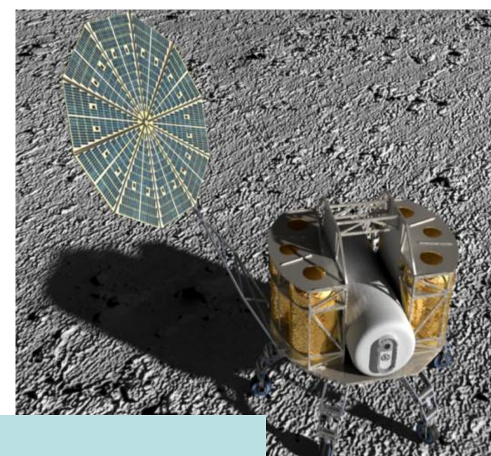


Top Technology Development Driver

- **Potential Requirements**
  - Modular power system
  - ~20-40 kW lunar daytime power level
  - ~10-20 kW lunar nighttime power level
  - 5,000 hr operational life at poles
  - >10,000 hr operational life beyond poles
  - 5-10 year calendar life
  - 100 -1000+ discharge/recharge cycles
  - Thermal, dust, launch/landing, vacuum environments
  - Autonomous control and operation
  - Human-rated
  - Low mass and volume
  - Little or no maintenance needs

Energy Storage: Regenerative Fuel Cells

- ~250 $kWhr_{net}$ energy storage module
  - Equals ~2 kW_{net} minimum fuel cell continuous power at Shackleton Crater
- ~36 cell fuel cell stacks,
  ~18 cell electrolyzer stacks
  - Based on ~30 Vdc bus voltage
- Cryogenic vs Gaseous reactant Storage



Prioritized mission requirements:
Reliable, long-duration maintenance-free operation; human-safe operation; architecture compatibility; high specific-energy; high system efficiency.

Converting Constellation Architecture into Tech Development Goals
Example: Surface Mobility Systems (nominal missions)

4 classes of rover missions:

- Short duration outpost traverse (Chariot)
- Long duration pressurized crewed sortie (Small Pressurized Habitat + Chariot)
- Long duration habitat transport (ATHLETE)
- Science/ISRU platforms

Power profiles differ for each, but each include some subset of the following functions:

- Pre-sortie vehicle check-out, transport to site(s), return transport,
  post-sortie checks and shutdown;
- Ingress/egress time for each EVA, boots-on-surface time, crew time in rover;
- Robotic lifting, connecting, emplacement, testing, processing.

Example: Short- and long-term pressurized rover

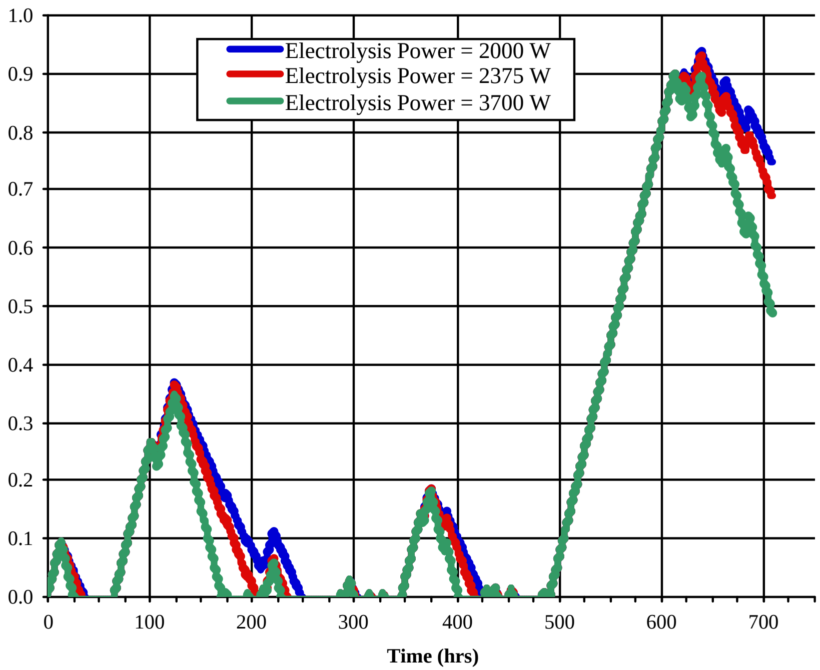
Length of Sortie (days)	Sorties per year	Energy per sortie per rover (kW-hr)	Energy from Fuel Cell (per sortie, per rover) (kW-hr)	Energy from Battery (per sortie, per rover) (kW-hr)
1	48	22	-	22
3	12	104	-	104
7	10	307	250	57
14	6	557	500	57

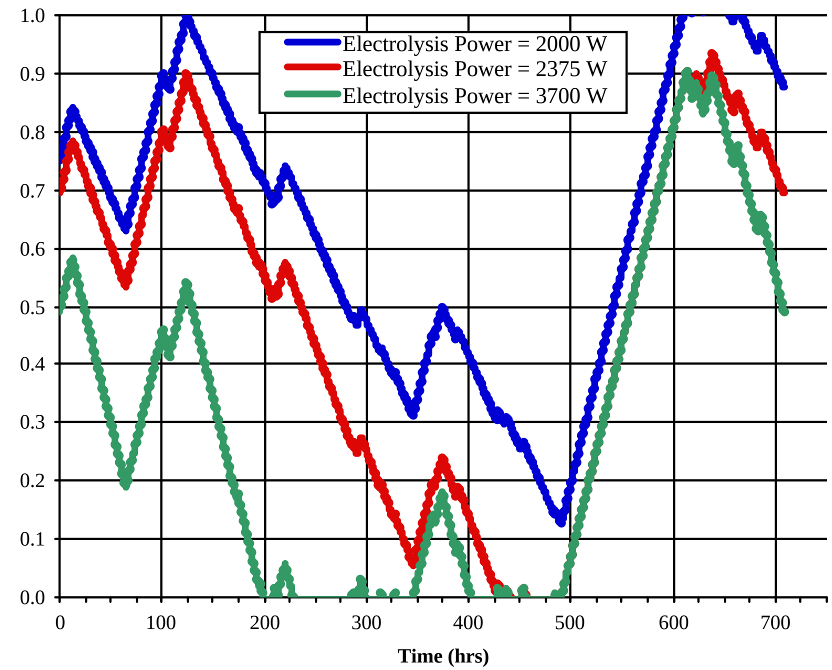
Ref: Commonality of Electrolysis Sub-Systems for ISRU, Power, and Life Support for a Lunar Outpost, D.L. Linne et al (2008)

Human-safe operation; reliable, maintenance-free operation; architecture compatibility; high specific-energy.

RFC fuel-cell reactant tank Depth-of-Discharge over the course of a month for Electrolysis power = 2kW (blue), 2.375kW (red), and 3.7kW (green)

Depth of Discharge (%)
(0 – 100% shown)





Time (hours) (0 – 700 hours shown)

Left plot assumes tanks start full.

Right plot assumes tanks are depleted after September.

Assumes 66% fuel cell efficiency and 84% electrolyzer efficiency, operation at Shackleton Crater in September and October, 2020.
Ref: Commonality of Electrolysis Sub-Systems for ISRU, Power, and Life Support for a Lunar Outpost, D.L. Linne et al (2008)

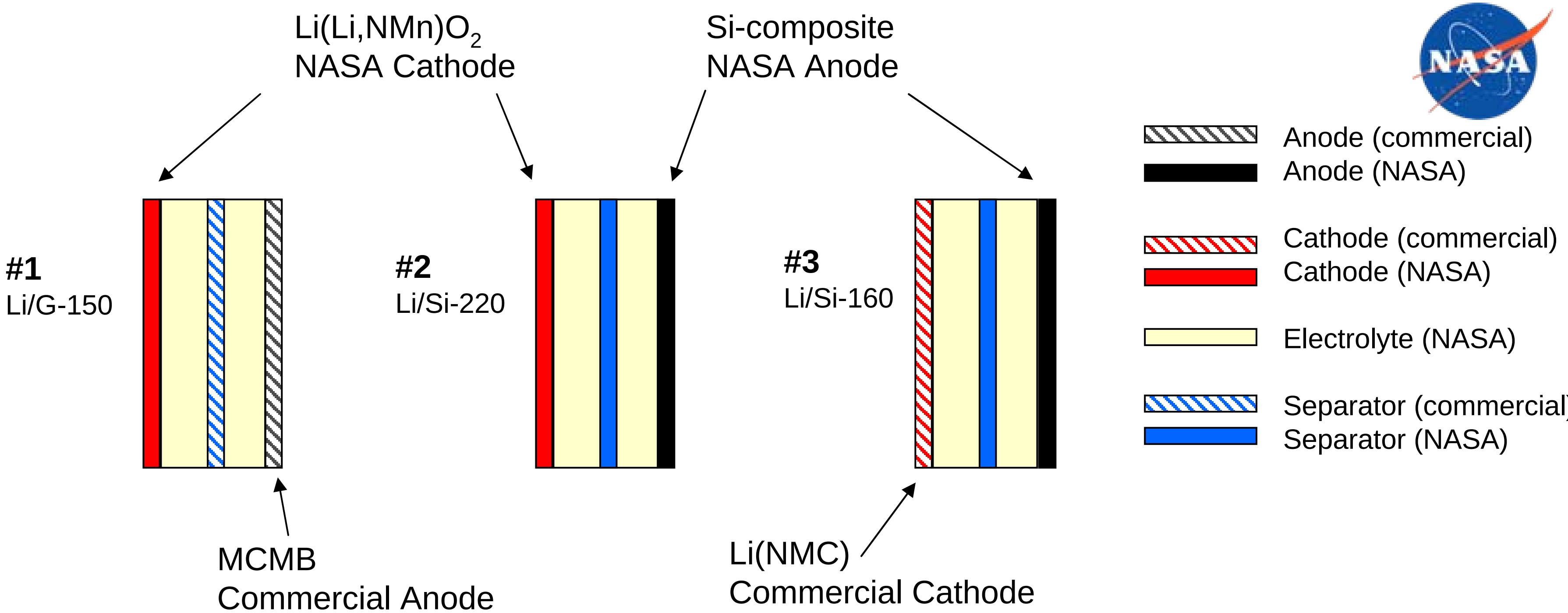
Key Performance Parameters for Battery Technology Development
Derived Values Based on Customer Requirements

Customer Need	Performance Parameter	State-of-the-Art	Current Value	Threshold Value	Goal
Safe, reliable operation	Electrolyte flammability	Controllers used to prevent unsafe conditions. There is no non-flammable electrolyte in SOA	Preliminary results indicate a moderate reduction in the performance with non-flammable additives	Non-flammable electrolyte that will minimize thermal runaway	Tolerant to mild abuse, overcharge and over-temperature
Specific energy Lander: 150 – 200 Wh/kg (14KWhr, 67 kg, 45L, 10 cycles) Rover: 150 – 200 Wh/kg EVA: 200 – 300 Wh/kg 100 cycles	**Battery-level** specific energy*	90 Wh/kg at C/10 & 30°C 83 Wh/kg at C/10 & 0°C (MER rovers)	105 Wh/kg at C/10 & 30°C 95 Wh/kg at C/10 & 0°C	**135** Wh/kg at C/10 & 0°C "High-Energy"** **150** Wh/kg at C/10 & 0°C "Ultra-High Energy"**	**150** Wh/kg at C/10 & 0°C "High energy" **220** Wh/kg at C/10 & 0°C "Ultra-High Energy"
	Cell-level specific energy	130 Wh/kg at C/10 & 30°C 118 Wh/kg at C/10 & 0°C	150 Wh/kg at C/5 and 0ºC	**165** Wh/kg at C/10 & 0°C "High Energy" **180** Wh/kg at C/10 & 0°C "Ultra-High Energy"	**180** Wh/kg at C/10 & 0°C "High energy" **260** Wh/kg at C/10 & 0°C "Ultra-High Energy"
	Cathode-level specific capacity $Li(Li,NiMn)O_2$	140 – 150 mAh/g typical	$Li(Li_{0.17}Ni_{0.25}Mn_{0.58})O_2$: 240 mAh/g at C/10 & 25ºC $Li(Li_{0.2}Ni_{0.13}Mn_{0.54}Co_{0.13})O_2$: 250 mAh/g at C/10 & 25ºC 200 mAh/g at C/10 & 0ºC	**260** mAh/g at C/10 & 0°C	**280** mAh/g at C/10 & 0°C
	Anode-level specific capacity		320 mAh/g MCMB 450 mAh/g Si composite	**600** mAh/g at C/10 & 0°C With Si composite	**1000** mAh/g at C/10 0°C With Si composite
Energy density Lander: TBD Rover: TBD EVA: ~400 Wh/l	**Battery-level** energy density	250 Wh/l	n/a	**270** Wh/l "High Energy" **360** Wh/l "Ultra-High"	**320** Wh/l "High Energy" **420** Wh/l "Ultra-High"
	Cell-level energy density	320 Wh/l	n/a	**385** Wh/l "High Energy" **460** Wh/l "Ultra-High"	**390** Wh/l "High Energy" **530** Wh/l "Ultra-High"
Operating environment 0ºC to 30ºC, Vacuum	Operating temperature	-20ºC to +40ºC	-50ºC to +40ºC for all carbonate- and ester-blend electrolytes in prototype cells	**0ºC** to **30ºC**	**0ºC** to **30ºC**

Assumes prismatic cell packaging. Goal values assume lightweight battery construction.

* Battery values are assumed at 100% DOD, discharged at C/10 to 3,000 volts/cell, and at 0 degrees C operating conditions

** "High-Energy" = NASA-developed Li(Li,NMn)O2 cathode with MCMB graphite anode
"Ultra-High Energy" = NASA-developed Li(Li,NMn)O2 cathode with Silicon composite anode



Cell 1: Li(NMn)/MCMB-150 “High Energy”
Baseline for EVA and Rover
Lithiated-mixed-metal-oxide cathode / Graphite anode
Li(Li,NMn)O_2 / Commercial mesocarbon microbead
150 Wh/kg @ battery-level 0^0C C/10, ~2000 cycles at 100% DOD

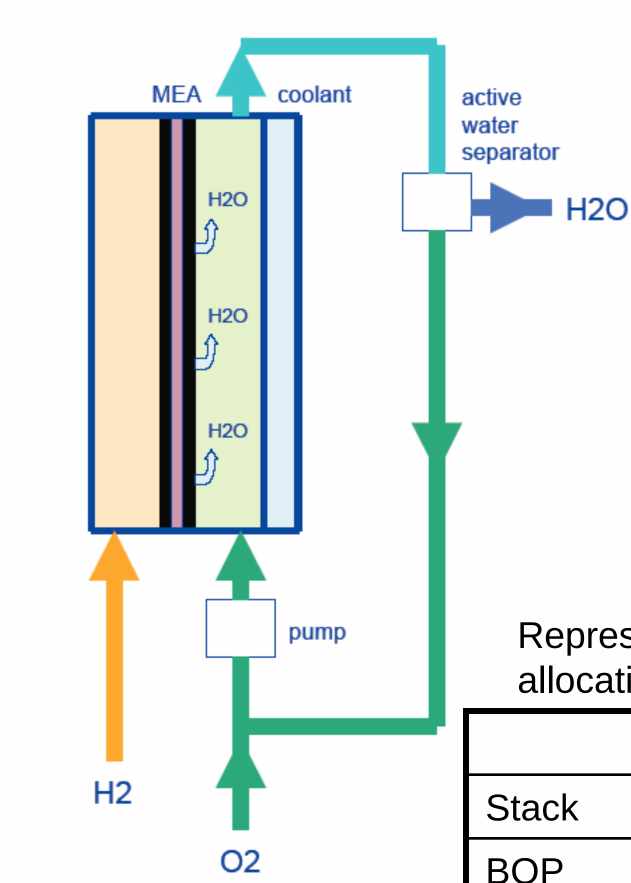
Cell 2: Li(NMn)/Si-220 “Ultra-High Energy”
Upgrade for EVA and Altair, possibly Rover
Lithiated-mixed-metal-oxide cathode / Silicon composite anode
Li(Li,NMn)O_2 / silicon composite
220 Wh/kg @ battery-level 0^0C C/10, ~200 cycles 100% DOD

Cell 3: Li(NMC)/Si-160 (virtually no-cost option)
Lithiated-mixed-metal-oxide cathode / Silicon-composite anode
Commercial Li(Li,NMC) / Silicon composite anode
160 Wh/kg @ battery-level 0^0C C/10, ~200 cycles 100% DOD

Proton Exchange Membrane Fuel Cell
Design Options

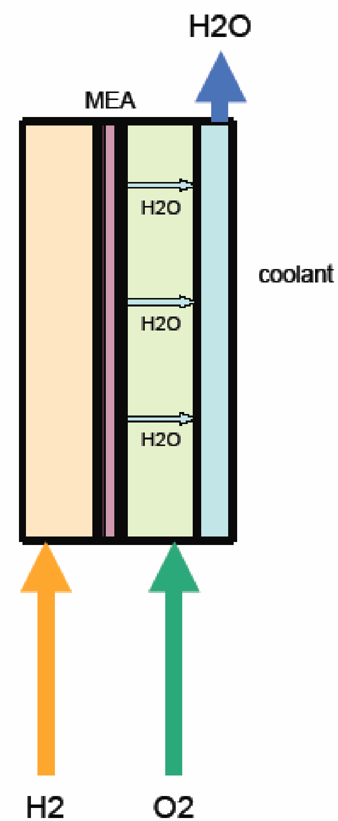
“Flow-Through”
Conventional design.
Used widely in terrestrial applications because venting is required to purge non-O2 air constituents.
Pump and separator are life-limiting elements of this design.

“Non-Flow-Through”
Membrane wicks water through;
Eliminates external pumps and separators.
This design was used on the Gemini capsule.



Representative mass allocation for 3 kW fuel cell

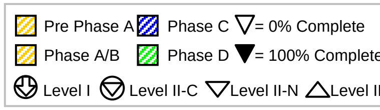
	FT	NFT
Stack	16 kg	13 kg
BOP	21 kg	9 kg
Total	37 kg	22 kg



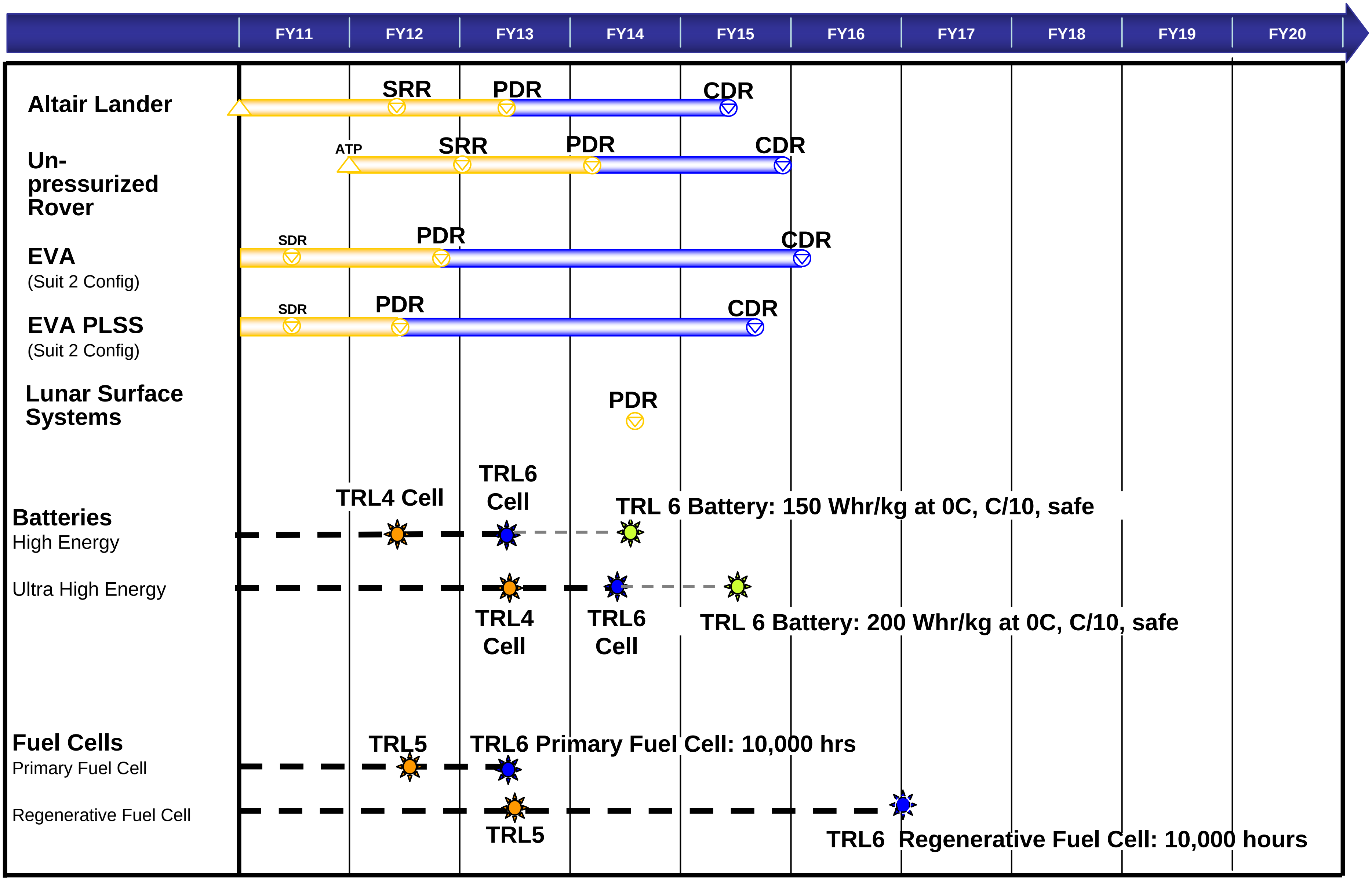
Key Performance Parameters for Fuel Cell Technology Development
Derived Values Based on Customer Requirements

Customer Need	Performance Parameter	SOA (alkaline)	Current Value	Threshold Value	Goal
Lander: 3 kW for 220 hours continuous, 5 kW peak. Lunar Surface Systems: TBD kW for 15 days continuous Rover: TBD	System power density @ nominal power (3 kW)				
	Flow-Through Fuel Cell	49 W/kg	33 W/kg	65 W/kg	81 W/kg
	Non-Flow-Through Fuel Cell	n/a	n/a	88 W/kg	136 W/kg
	RFC (without tanks)	n/a	11 W/kg	25 W/kg	36 W/kg
	Stack power density @ nominal power (3 kW)				
	Flow-Through Fuel Cell	97 W/kg	132 W/kg	97 W/kg	188 W/kg
	Non-Flow-Through Fuel Cell	n/a	n/a	107 W/kg	231 W/kg
	Balance-of-plant mass (3 kW system)				
	Flow-Through Fuel Cell	30 kg	n/a	30 kg	21 kg
	Non-Flow-Through Fuel Cell	n/a	n/a	21 kg	9 kg
**Stack efficiency values assume 200 mA/cm^2 operation.	Stack efficiency**				
	Flow-Through Fuel Cell	73%	70%	71%	73%
	Non-Flow-Through Fuel Cell	n/a	67%	71%	73%
	System efficiency				
	RFC	n/a	n/a	46%	56%
Maintenance-free lifetime Lander: 220 hours (primary) Surface: 10,000 hours (RFC)	Fuel cell system maintenance-free operating life				
	Flow-Through Fuel Cell	2500 hrs	1000 hrs	5,000 hrs	10,000 hrs
	Non-Flow-Through Fuel Cell	n/a	n/a	5,000 hrs	10,000 hrs
	RFC	n/a	n/a	5,000 hrs	10,000 hrs

Constellation Program
Summary Schedule
Lunar Capability Content



PMR '07 Baseline – 10/19/07



Summary: Technology Development Goals for the Lunar Surface and Lander

LAT-1 and LAT-2 identified regenerative fuel cells and rechargeable batteries as enabling technology, where enabling technologies are defined as having:
"overwhelming agreement that the program cannot proceed without them."

Surface Systems

Surface Power:	Maintenance-free operation of regenerative fuel cells for >10,000 hours using ~2000 psi electrolyzers. Power level TBD (2 kW modules for current architecture) Reliable, long-duration maintenance-free operation; human-safe operation; architecture compatibility; high specific-energy, high system efficiency.
Mobility Systems:	Reliable, safe, secondary batteries and regenerative fuel cells in small mass/volume. 200 W-hr/kg assumed; 150 W-hr/kg may be sufficient. Human-safe operation; reliable, maintenance-free operation; architecture compatibility; high specific-energy.

EVA

	Portable Life Support System (PLSS); and Power, Communications, Avionics, and Informatics (PCAI) Subsystem: 200 – 300 W-hr/kg; ~400 Wh/liter Human-safe operation; 8-hr duration; high specific energy; high energy-density.

Lunar Lander

Ascent Stage:	Rechargable battery capability for ascent operations and to support emergency lander/surface operations. Nominally 14 kWhr in 67 kg, 45 liter package. Human-safe, reliable operation; high energy-density.
Descent Stage:	Functional primary fuel cell with 5.5 kW peak power. Human-safe reliable operation; high energy-density; architecture compatibility.

Acknowledgements

The following people contributed data, images, text and/or ideas to this presentation:

Michelle Manzo
Mark Hoberecht
Concha Reid
Tom Miller
Dave Hoffman
Joe Nainiger
Rob Button
Diane Linne
Diane Malarik